LETHALITY CRITERIA FOR DEBRIS GENERATED FROM ACCIDENTAL EXPLOSIONS

Author : Mr Jon Henderson
Deputy Chief Inspector Explosives (MoD)
Fir 3 C, #4304
MOD Abbeywood, Bristol, BS32 8JH

ABSTRACT

The present criteria for the lethality of debris is based on work by conducted in the early part of the last century. The criteria for converting this lethality into separation distances for explosives storage is somewhat less clear but appears to be based on a conditional probability of lethality of around 1%. Investigations have indicated that the actual probability is considerably less than this level.

This paper compares the criteria for establishing Inhabited Building Distances for the various Hazard Divisions and the different inherent explosion effects and recommends new criteria for use with HD 1.1 debris and details what effect this would have on the current QD tables.

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Mr Jon Henderson

Deputy Chief Inspector Explosives (MoD)
UK Ministry of Defence
MOD Abbeywood, Bristol, BS32 8JH

Introduction

1. Recent work by the UK (Ref 1) to investigate the development of Quantity Distance (QD) rules for small quantities of explosives in structures has led to serious questions regarding the potential lethality of secondary debris generated from the structures in question. The present approach is to assume that projected debris with a kinetic energy (KE) of more than 79 Joules is potentially lethal. For definition of Inhabited Building Distances (IBD) it is unacceptable that such debris occurs in a greater density than 1 per 55.7 sq m (generally as measured on the ground). Concerns have been raised in UK and NATO over defining the actual lethality as well as the density of the projections.

Aim

2. The aim of this paper is to set out the background to the present criteria and to lay out an argument for changing it to a more consistent and logical basis with the ultimate aim of recommending new criteria which could be used for the setting of any future debris based QDs.

Previous Studies

3. In 1983 the US Army Ballistic Research Laboratory, Maryland, employed a contractor (Ketron) (Ref 2) to survey the available literature as part of an investigation into the use and applicability of the US 58 ft lb blunt trauma criterion (58 ft lb converts to 78.64 Joules). Several hundred technical reports and journal articles were compiled, reviewed and analyzed. During the search there appeared to be a natural division between penetrating and non-penetrating injury data with the overwhelming majority of data and models relating to penetrating injury phenomena. All major sources of information in the US were consulted and there is no reason to suggest that any significant information was overlooked.

4. The report states that the literature abounds with references to the 58 ft lb energy criterion. Rohne (Ref 3) is usually given credit for establishing the criterion which the 1984 US paper suggests was probably never intended to be any more than a rough rule of thumb. The date usually attributed to its origin is 1906. The actual quote is “to remove a human from the battlefield a kinetic energy of 8mkg is sufficient according to the prevailing view of the German artillery community”. An earlier article by Rohne, written in 1896 under the same title, contains the same statement. In neither case does he cite

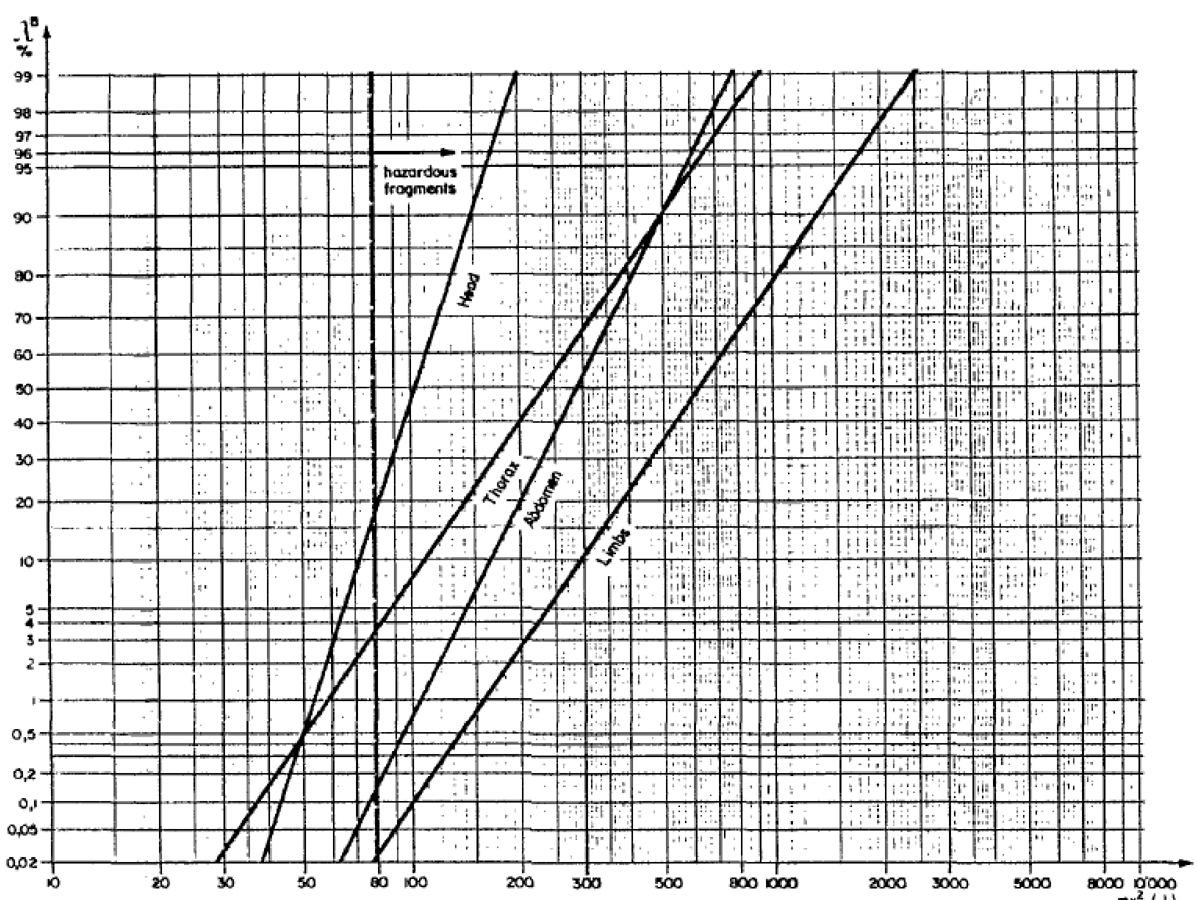
any data, experimental or otherwise, to substantiate this view. Rohne used the criterion to determine ranges at which various military rifles ceased to be effective. It is recommended that the 1984 paper by Neades should be consulted by anyone interested in the derivation of the KE criterion for incapacitation.

5. As an aside it is interesting how history has a tendency to get stood on its head when subjected to repeated analyses. The KE criterion as suggested by Rohne et al was set at 80 J. Over the years this seems to have been approximated to 58 ft lbf which has itself been equated to 79 J.

6. The primary conclusion of this report was that a viable solution to the problem of determining far field fragment hazards to personnel could involve simultaneous application of models to quantify the potential for both penetrating and non-penetrating injury with a hazardous condition being indicated if either criterion was met.

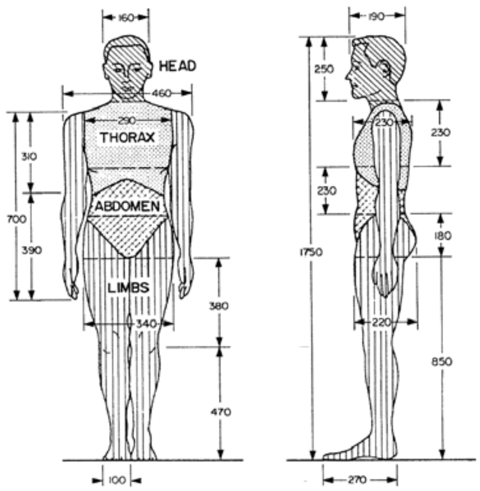
7. What the report really indicates is that the currently accepted criterion for lethality is in reality an incapacitation criterion and various other investigators work show how difficult it is to relate some sort of ballistic dose to the projectile's casualty producing potential. The reality is that much effort has been expended on understanding skin penetration as the primary incapacitation criterion and that the hazard from non-penetrating debris is not very well understood.

8. The graph below is reproduced from a Swiss paper to the 1982 DDESB Explosives Safety Seminar (Ref 4)



9. It shows probably the easiest to understand interpretation of the available data for lethalities associated with non-penetrating debris, established from various literature sources quoted in the Swiss document. It also shows the 79 Joule criterion used by NATO. The graph clearly illustrates that this criterion overestimates the effects of non-penetrating debris.

10. In the Swiss model the location of an impact is accounted for by dividing the body into four primary regions for which the lethality of impacts is shown in the graph.



11. The most recent attempt to put some more validity on the 58 ft lb criterion is contained within the US TP 21 (Ref 5). This documents the procedures for the collection, analysis and interpretation of explosion produced debris which at figure 11 presents a curve of kinetic energy versus probability of fatality. This is reproduced below.

12. What the figure clearly indicates is that a non penetrating fragment with an energy of 79 Joules only has a 31% probability of being lethal. An impact energy of some 103J would be required to make the fragment even 50% lethal. Of course it has to be realised that these are "average" values and the actual level of lethality will depend, not only on the impact energy, but perhaps more importantly on :

a. the condition and age of the "target", with obviously the very young or old being the most affected. The assumption is that the "target" is male, aged 20-50 and in good robust health.
b. the position of impact, with impacts on the head and upper chest area being potentially the most lethal

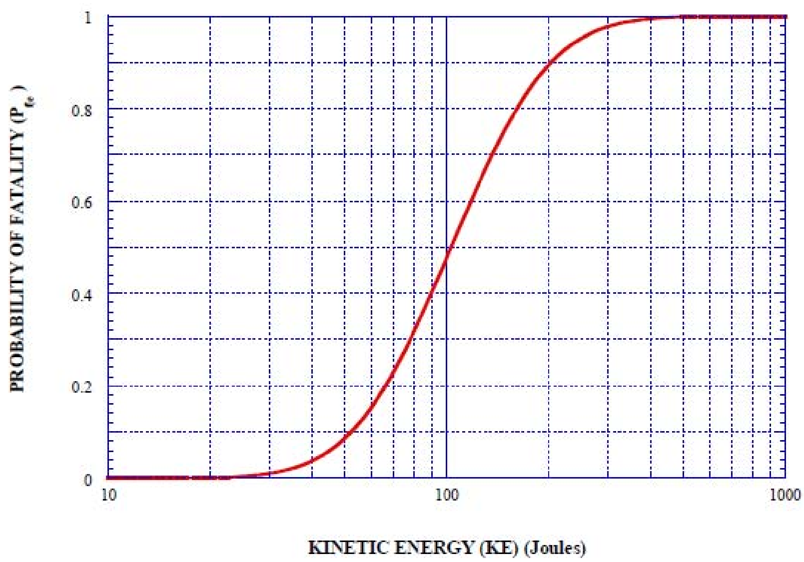


FIGURE 11. KINETIC ENERGY VERSUS PROBABILITY OF FATALITY

13. It is interesting to compare these figures with the graph produced from Switzerland. That suggested an 80 J criterion is about 20% lethal for strikes to the head and about 4% ;lethal to the thorax area. For 90% lethality the necessary energy is about 150J to the head and 500J to the thorax. Although difficult to compare directly with the US graph it can be seen that they lie in the same area and agree that the current lethality criterion is somewhat conservative.

14. The concept of being killed by a blunt, i.e. non-penetrating, impact is very difficult not only to quantify but also to relate to reality. After much research in the sports area it has been ascertained that various ball sports where the ball could impact the player's body give rise to levels of impact energy as shown in the table

Projectile type	Mass (g)	Typical velocity (m/s)	Typical KE (J)
Cricket Ball	156-163	Max 42	140
Baseball	142-149	Max 45	145
Tennis Ball	56-59	Max 65	120
Golf Ball	45	Max 76 (in testing)	130

15. As a comparison there are numerous documented instances of players being killed by cricket balls to the head, and several to the upper body or thorax area. There are also instances of similar fatalities from impacts of baseballs but not apparently as numerous. Instances from golf are even rarer and it is very difficult to ascertain what the levels of

impact energy for a golf ball might be. The figure quoted in the table above is derived from the fastest speed of a golf ball leaving the golf club head as measured in testing. There is no recorded value for potential impacts. Golf is, of course, significantly different from the other sports quoted in that there is no deliberate intent to fire the ball at the opponent and those instances of injury and fatality in golf are normally to people removed at much greater distances from the golf ball driver that happens in any of the other sports. The interesting one is tennis where there have been instances of injury from impacting tennis balls but no serious injuries and certainly no fatalities – one complicating factor is that a tennis ball is much "softer" than any of the other balls quoted and it is probable that the energy transfer mechanism from a ball which deforms significantly on impact results in a much lower impact energy.

16. What has not been possible is to synthesise a probability of fatality as the incidence of non fatal impacts in the various sports is largely not documented. However there is no reason to suggest that it would not follow a very similar distribution to that shown in the graph above from Ref 5.

Trials Data

17. Thus far the primary thrust of this paper has only addressed one part of the lethality equation – the kinetic energy of the fragment/debris when it strikes the target and how lethal this effect is. However the other key component, the number and density of such fragments, is generally derived from trials data with a whole set of accompanying new problems.

18. The major problem with analysing any trials debris data is how to assess its lethality from which the appropriate IBDs can be deduced. Throughout NATO the criteria normally associated with consideration of debris hazard for Inhabited Building Distance purposes is to consider that any explosion generated debris with an energy in excess of 79 Joules is potentially fatal and that it should not occur with a density in excess of 1 per 56 square metres as measured on the ground. Although these criteria have been the subject of discussion over the years no better criteria have ever been proposed.

19. There have been various approaches suggested as to how best to represent the "real" hazard from debris. These are detailed in an AC326 document (Ref 6). One of the considerations is the method used for actual pickup of the debris after an explosives trial. In almost all the trials data considered in the UK review the debris was collected and therefore analysed in 10 degree wide 20 m deep sectors. The only exceptions were the earlier of the 1980s trials which were limited generally to 2 degree wide sectors, but still generally 20 m deep. More recent debris trials (which used large NEQs) have identified debris position by range and bearing thus potentially allowing a study of the effects of different sizes of pickup areas. However to maintain consistency with earlier analyses this data has been reduced to similar 10 degree wide 20 m deep sectors for actual analysis.

20. The key issue is how to actually calculate the density of the debris generated. The only information available from the trials is the mass and final resting position by sector (as described above) of the debris. In some trials there is detailed (but limited) information on the variation in mass and actual size of debris pieces collected by sector. In most circumstances only the total number of pieces either within a mass bin or over a certain mass/size are available for each sector.

21. It should be obvious that any piece of debris will have zero residual energy at its final resting position. What is not so obvious is at what range its energy dropped below the defined 79 Joules. What is also not obvious is whether any account needs to be taken of debris that might have passed through the area. This is particularly relevant in circumstances where the debris is expected to be projected horizontally as the "target" against which the lethality is being measured is a standing person. In far field considerations the target is taken as a standing person presenting a target cross section area of some 0.5 sq m to the incoming fragment which is assumed to be falling at or near to the vertical.

Conclusions

22. Despite all the evidence no change has ever been seriously proposed let alone subject to serious technical discussion in open forum. What does not help either is that the 79 Joule criterion is applied to the definition of IBD. The primary criterion for IBD is that the expected blast effect should not exceed 5 kPa. This in turn has been derived from a knowledge of the effects of blast on buildings and is indeed why it is referred to as an Inhabited Building Distance. The key phrase is "Inhabited Building". It is very difficult to ascertain the lethal effect of such a low level of pressure and in reality it would not be expected to be lethal directly but could cause fatalities if the person were unfortunate enough to be standing in front of a single glazed (made of say 4mm annealed glass) window of a reasonable size when the pressure was applied. It is well documented that current UK double glazing standards would prevent any such injuries at these pressure levels.

23. It is not clear why a protection criterion to personnel in the open should then be applied as an IBD bearing in mind that when we apply external QDs it is to exposed sites which are generally occupied buildings. What might be somewhat more logical would be the development of a debris criterion which addresses damage to buildings.

24. A way of achieving this might be to look at glazing damage from debris and relate it to the damage created by blast overpressure. Given that a KE of 79 Joules would be more than sufficient to break most glazing panels this would give some more credibility to the energy criterion. However the density of such fragments would have to be raised significantly to ensure that sufficient debris reaches the target to give a similar level of breakage to that from the overpressure. This highlights one of the difficulties of looking at debris effects which is that it is very probabilistic as not all targets see the same debris effect at any specific range from the PES whereas with overpressure all targets see exactly the same effect. However, given that the front face of a house probably has some

20% of its surface area glazed, intuitively it would require at least a five fold increase in the fragment density (and probably more like an order of magnitude) to “ensure” an equivalent level of damage. Such a re-analysis of existing trials debris data is quite feasible and would automatically result in the debris IBD being much smaller than the blast related IBD (provided that one uses the NATO formula of $22.2Q^{1/3}$ to calculate the blast qd) throughout the range of NEQs the qd tables cater for.

25. Perhaps the most obvious way of changing the criterion is to consider what an acceptable level of lethality might be. At the outset a value of 1% probability (conditional) of fatality was quoted as being the assumption behind the current criterion based on the supposition that the 79 Joule fragment is generally considered lethal above this value and non-lethal when below it. The reader will realise that this is vastly oversimplified but it serves to illustrate a potential solution. If the assumption is indeed that such a fragment attack is indeed lethal then inspection of the earlier diagram published by the US in their TP15 and corroborated by most researchers in the area would suggest that the KE criterion could be lifted to either 100J, giving a lethality of 50%, or even to 200J, giving a lethality of 95+%. The alternative might be to increase the density of the original 79 J fragment to give the same effect. Assuming the original lethality at 30% would result in densities of around 3 or 6 depending on the lethality level chosen. In most circumstances this is likely to lead to the debris IBD always being significantly less than the blast IBD again provided that one uses the NATO formula of $22.2Q^{1/3}$ to calculate the blast qd.

26. Allied to either of these approaches could be the development of complimentary qds for personnel in the open. If the criterion is set at 1% level of lethality as acceptable then using the above logic trail would yield the appropriate qds.

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1. PFP(AC326-SG5)(GBR)IWP 01-2009 dated 13 Feb 2009-08-14

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3. Rohne, H ; Schiesslehre fur Infantrie, 1906

4. 1982 DDESB Explosives Safety Seminar, “Lethality of Unprotected persons due to Debris and Fragments”, P W Janser

5. DDESB TP 21 dated 22-10-2007

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Deputy Chief Inspector Explosives (MoD)
UK Ministry of Defence
E-mail : DESWpnseng-DCIE@mod.uk

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The present approach is to assume that projected debris with an energy of more than 79 Joules is potentially lethal.

For definition of IBD it is unacceptable that such debris occurs in a greater density than 1 per 55.7 sq m (generally as measured on the ground).

Concerns have been raised in UK and NATO over defining the actual lethality as well as the density of the projections.

Rohne, H ; Schiesslehre fur Infantrie, 1906

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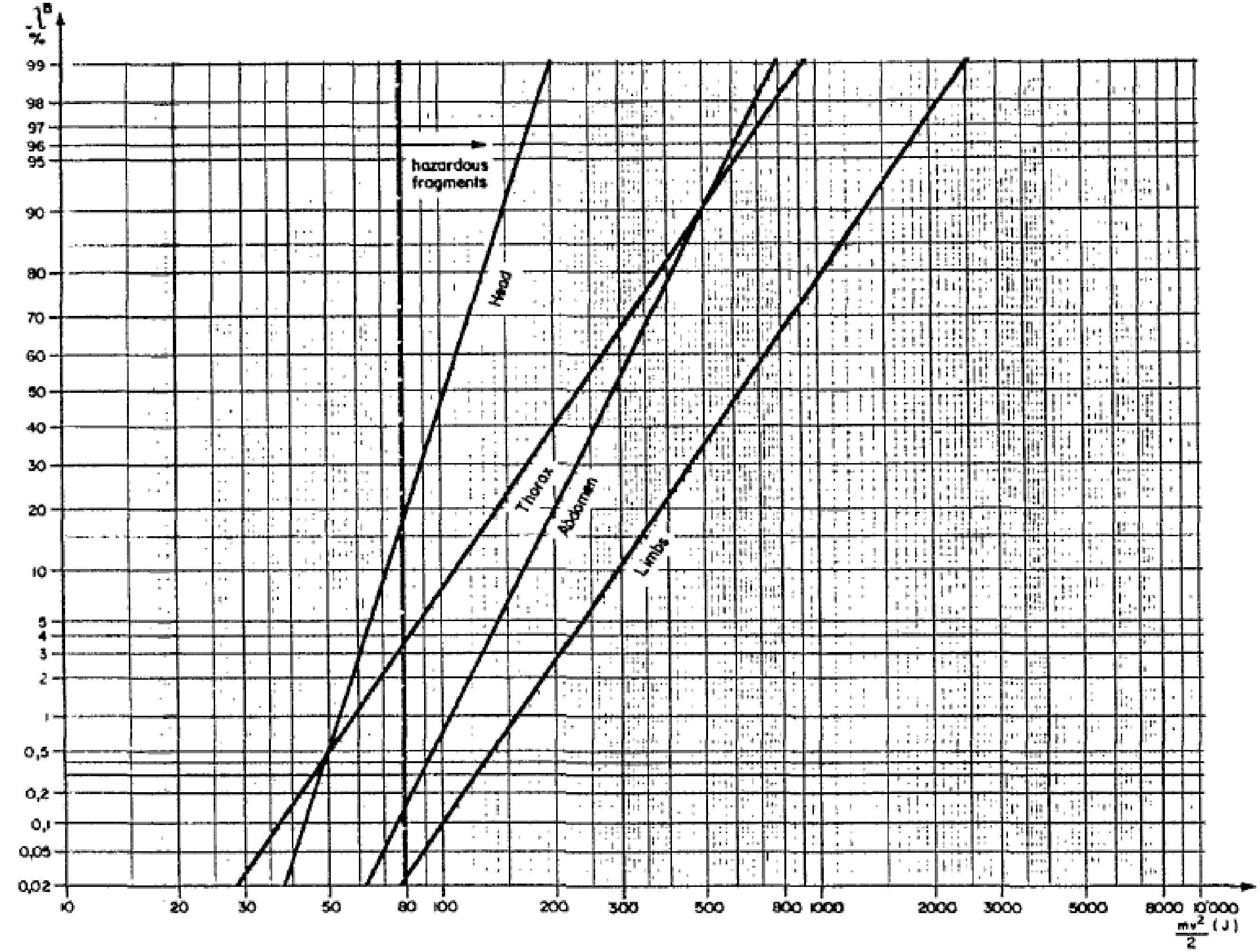
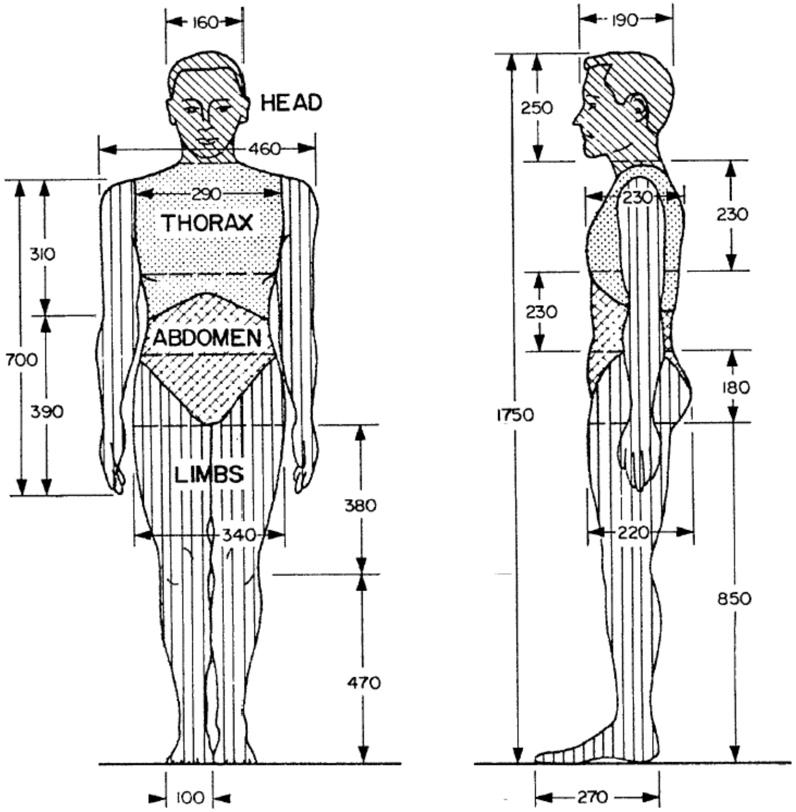


%
99
98
97
96
95
90
80
70
60
50
40
30
20
10
5
4
3
2
1
0,5
0,2
0,1
0,05
0,02
hazardous fragments
Head
Thorax
Abdomen
Limbs
10
20
30
50
80
100
200
300
500
800
1000
2000
3000
5000
8000
10'000
$\frac{mv^2}{2}$ (J)



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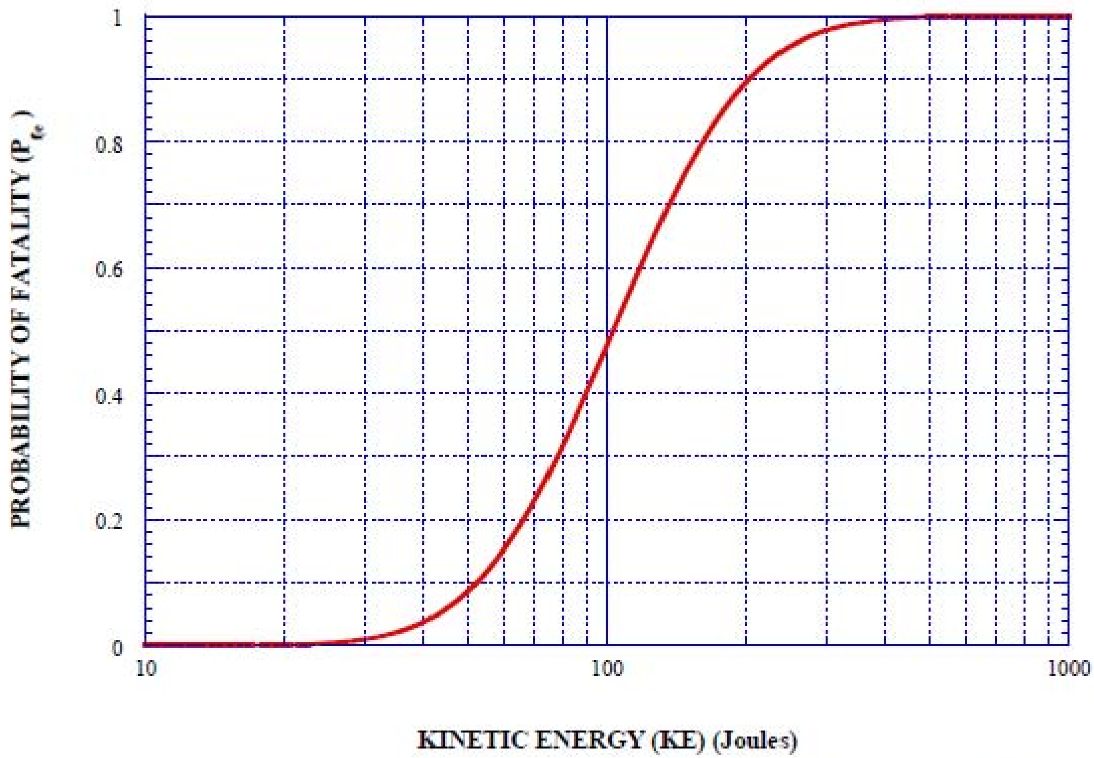

FIGURE 11. KINETIC ENERGY VERSUS PROBABILITY OF FATALITY

Energy of 79 Joules only has a 31% probability of being lethal.

An impact energy of some 103J would be required to make the fragment even 50% lethal.

Actual level of lethality will depend, not only on the impact energy, but perhaps more importantly on :

1.the condition and age of the “target”, with obviously the very young or old being the most affected. The assumption is that the “target” is male, aged 20-50 and in good robust health.

2.the position of impact, with impacts on the head and upper chest area being potentially the most lethal

Projectile type	Mass (g)	Typical velocity (m/s)	Typical KE (J)
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Baseball	142-149	Max 45	145
Tennis Ball	56-59	Max 65	120
Golf Ball	45	Max 76 (in testing)	130

Trials Data

How do we assess lethality from which the appropriate IBDs can be deduced.

IBD defined as position where there is no more than 1 potentially fatal fragment per 56 square metres.

How best to represent the “real” hazard from debris.

The only information available from the trials is the mass and final resting position by sector of the debris.

It should be obvious that any piece of debris will have zero residual energy at its final resting position.

What is not so obvious is at what range its energy dropped below the defined 79 Joules.

What is also not obvious is whether any account needs to be taken of debris that might have passed through the area.

IBD is traditionally associated with blast overpressure effects

Debris criterion is to unprotected personnel in the open

Can we correlate the two effects

Glazing damage??

What about the 1% level

Develop QDs specifically for unprotected personnel

PROPOSED SMALL QUANTITY INHABITED BUILDING DISTANCES FOR MASONRY BUILDINGS

NEQ(Kg)	Traversed IBD (m)	Untraversed IBD (m)
< 0.1	0	0
1	6	12
5	28	58
10	54	115
25	135	155
50	160	230
100	200	255
150	230	290
200	260	325
250	285	355
300	305	365
400	340	385
500	375	400

POTENTIAL SMALL QUANTITY IBDs FOR MASONRY BUILDINGS USING REVISED DENSITY CRITERIA

NEQ(Kg)	Traversed IBD (m)		Untraversed IBD (m)	
	Revised density criteria (3 per 56 sq m)	Original density criteria (1 per 56 sq m)	Revised density criteria (3 per 56 sq m)	Original density criteria (1 per 56 sq m)
< 0.1		0		0
1		6		12
5		28		58
10		54	105	115
25	115	135	140	155
50	145	160	155	230
100	185	200	220	255
150		230	235	290
200		260		325
250	230	285		355
300		305		365
400		340		385
500	280	375	370	400

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POTENTIAL CHANGES TO IBDs FOR MASONRY BUILDINGS USING REVISED ENERGY CRITERIA

NEQ(Kg)	Traversed IBD (m)		Untraversed IBD (m)	
	Revised energy criteria (200J)	Original energy criteria (80J)	Revised energy criteria (200J)	Original energy criteria (80J)
500	340	375	400	440
1800	290	370	500	520
5600	430	480	530	530

POTENTIAL SMALL QUANTITY IBDs FOR MASONRY BUILDINGS USING FURTHER REVISED DENSITY CRITERIA

NEQ(Kg)	Traversed IBD (m)			Untraversed IBD (m)		
	Revised density criteria (5 per 56 sq m)	Revised density criteria (10 per 56 sq m)	Original density criteria (1 per 56 sq m)	Revised density criteria (5 per 56 sq m)	Revised density criteria (10 per 56 sq m)	Original density criteria (1 per 56 sq m)
1			6			12
5			28			58
10			54	100	95	115
25	105	100	135	130	125	155
50	140	120	160	155	150	230
100	175	125	200	210	205	255
250	225	175	285	225	215	355
500	255	225	375	355	320	440
1800	235	115	370	390	345	520
5600	210	115	480	430	410	530

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